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ON CHONDRULES AND CHONDRITIC STRUCTURE IN METEORITES[1]

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The term "chondrit," from the Greek χονδρος, a grain, was first used, so far as I am aware, by Gustav Rose[2] to designate a class of stony meteorites characterized by the occurrence of small granules or "*kugeln*." "Sie ist durch kleine Kugeln ausgezeichnet die aus einem noch nicht bestimmten Magnesia-Silicate bestehen, und in einem fein kornigen Gemenge eingemengt sind," etc. The word, with the addition of the terminal *e*, as *Chondrite*, has been very generally adopted, with its original meaning, by English and American writers. Unfortunately, as it would seem, a further modification of the word as *chondros*, *chondrule*, *chondrus*, or *chondrum* has been introduced, at first apparently synonymous in meaning with *kugel* as used by Rose though it is to be noted that he did not define the word quite as clearly as might be desired. He wrote: "* * * in Bruche erscheinen sie *theils uneben*, *theils fasrig*, im letzern Fall jedoch stets nur sehr feinfaserig, indessen doch immer bestimmt erkennbar fasrig, besonders unter der Lupe * * nie radial, sondern immer excentrisch fasrig." No further reference is made to those of "*uneben* Bruche" and one is left only to surmise that they may have been of a granular or porphyritic rather than fibrous structure. The fact that Rose's work was written before the day of thin sections doubtless accounts for the undetermined character of the magnesian silicate.

Tschermak in his *Mikroskopische Beschaffenheit* (1885) was little more explicit in his use of terms than was Rose. He wrote: "Kugelchen und *überhaupt rundliche Körper*, welche bald aus einem einzigen krystallindividuum, bald aus mehreren bestehen, öfters auch aus verschiedenen Gemengtheilen zusammengestzt sind, bilden das Gestein fast allein (Borkut) oder sie lagern unverletzt, öfters auch zersplittert in einer lockeren bis festen Tuffmasse." Elsewhere he includes all the rounded forms under

the term *chondren,* though in his plate legends and descriptions he designates both as *Kugelchen,* thus using the two terms synonymously.

A perusal of the literature shows that by English and American writers, the terms *chondrule, chondrus, chondrum* or *chondros* are now and have for some years been applied to the rounded and oval granules presenting a considerable range in mineral composition and still wider range in internal structure, thus making the terms synonymous with kugel or kugelchen as used by Tschermak above. Of later years and as illustrated in the generally adopted scheme of classification,[3] there has seemed a disposition to use the term kugel in a descriptive adjective sense, as *kugelchen chondrit,* under which name are included stones containing chondrules (or chondri) having a radiate structure—the *spherulitic*[4] chondrites of American writers. There has thus apparently arisen in the minds of many a confusion which, as it seems to the writer, has been in part at least responsible for the diverse views expressed concerning the origin of these peculiar bodies. In other words, there has been a failure to recognize or discriminate between the *kugelchen* with radiate structure and the often irregular polysomatic forms with the "uneben Bruche."

The present paper, then, represents an attempt on the part of the author to make this discrimination and to show how far proposed theories may apply to the various forms presented.

NATURE OF THE CHONDRULE

At the outset and for the purpose of making clear what is to follow, it will be well to figure and describe a few characteristic forms of the individual chondrules. This notwithstanding the previous most excellent and comprehensive work of Tschermak and Cohen.[5]

Mineralogically, the chondrules, using the word in its broadest and most comprehensive sense, in nearly all meteorites are composed chiefly of the minerals olivine or pyroxene, the latter in either orthorhombic or monoclinic forms, or both. Some are largely of an undifferentiated glass. Feldspars occur but rarely except in the form known as maskelynite. In addition are occasional enclosures of metal or metallic sulphides, chromite or other minor constituents. The metallic iron sometimes occurs in rounded chondrite-like blebs, though it is doubtful if this should be referred to under that name. Structurally, the chondrules in the same meteorite may vary from densely cryptocrystalline, almost amorphous, to those that are part glassy and porphyritic or even holocrystalline.

I. *Glassy, Cryptocrystalline and Radiated Forms.*—In figures 1 and 2, are shown examples of cryptocrystalline forms from the stones of Barratta, Australia, and Cullison, Kansas. That of figure 1 is of a peculiar brownish translucency and very dense, resembling the "felsitic" structure of the early petrologist. In the Cullison stone, figure 2, the chondrules, also of a brownish color, are not completely isotropic but between crossed

nicols break up into several illy defined areas over which the dark cloud sweeps faintly and irregularly as the stage revolves. The material seems to be a partially devitrified glass in a condition of optical stress as from

FIG. 1

sudden cooling. Chondrules of this type and those next to be described more nearly resemble the spherulites of the terrestrial rocks than any others which have come under my notice. Their outlines are at times as sharply demarked from the matrix in which they are embedded as are

FIG. 2

the spherulites in the rhyolitic obsidians of the Yellowstone National Park.

Chondrules of the radiating type are shown in figures 3, 4 and 5, from the

meteorites of Elm Creek, Hessle, and Parnallee. The mineral in all cases is enstatite[6] and the outline of the spherule as sharp and clean as though it had been turned on a lathe. In the Elm Creek example crystallization

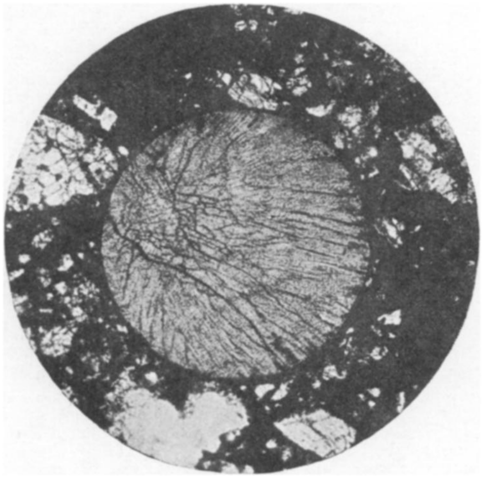

FIG. 3

evidently began at one point on the surface of the spherule and extended inward throughout, but the cooling proceeded too rapidly for the production of an optically perfect crystal. In the Hessle stone (fig. 4), there were evidently several initial points of crystallization. Forms like these

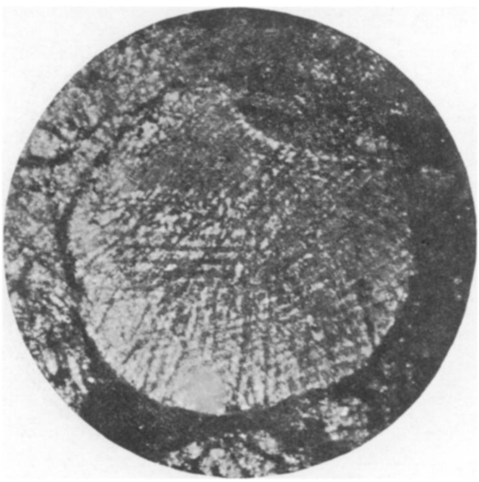

FIG. 4

grade imperceptibly into such as are shown in figure 5, in which the radiating bars have unmistakably the crystallographic properties of enstatite.

II. *Half Glassy, Barred and Porphyritic Forms.*—Porphyritic forms are

characteristic of both olivine and enstatite chondrules, while the barred forms, such as are shown in figures 6 and 7, are limited mainly, if not wholly, to monosomatic forms composed of olivine. In figure 6, from the

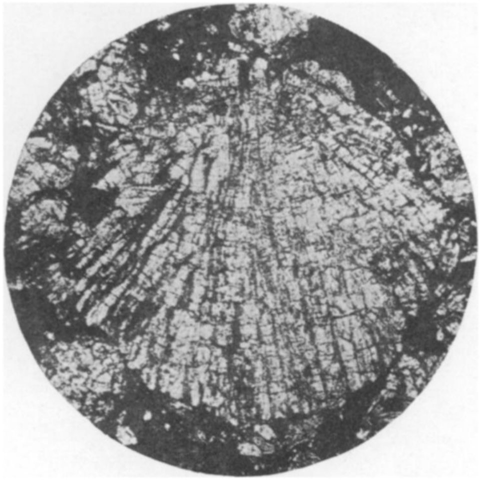

FIG. 5

Beaver Creek stone, the white portions are olivine which extinguish practically as a single unit; the black portions are glass. It is to be noted that the outlines, though sharp are not smooth as in those described above, but have projecting particles extending out into the ground; also

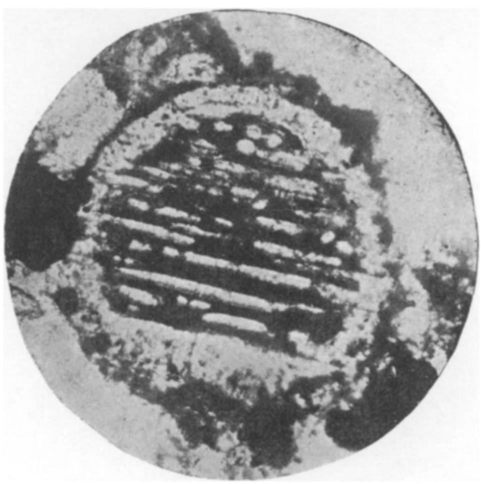

FIG. 6

that this border portion often contains enclosures. In figure 7 from the Hendersonville stone, the bars are bent and curved and do not all extinguish simultaneously, as the stage is revolved, the dark cloud sweeping

over it irregularly, indicating a condition of stress. Here, as in the last, the border is not sharply demarked from the ground and it is often impossible to state if a certain crystal particle belongs to one portion or the

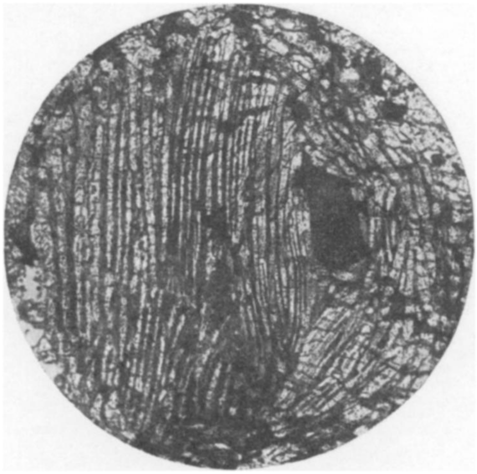

FIG. 7

other. It should be noted that this stone is a crystalline spherulitic chondrite. According to Tschermak, in chondrules of this nature the olivine bars are sometimes interlaminated with plagioclase (e.g., in the Dhurmsala stone). In the porphyritic form shown in figure 8 from the

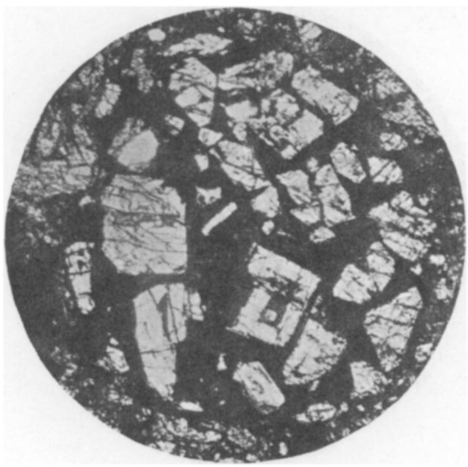

FIG. 8

Tennasilm stone, the granular ground abuts sharply against the black glass of the chondrule with only on one side a manifested tendency to penetrate into and beyond the border. It is to be noted that the enstatite

phenocrysts within the chondrule and near the border are often cut off sharply as though the sphere, originally much larger, had been uniformly reduced by abrasion. This will be referred to later.

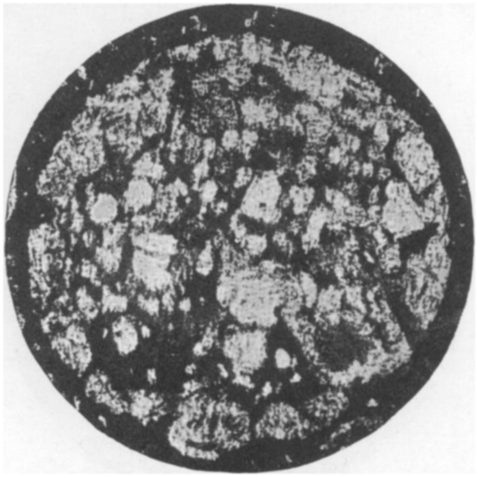

FIG. 9

III. *Holocrystalline Chondrules.*—As would naturally be expected, these porphyritic forms, through a reduction of the proportional amount of glass, pass gradually into those which are almost or quite holocrystalline and polysomatic as shown in figures 9 and 10 from the Barratta and Elm Creek stones respectively. Of peculiar interest are those of the polysynthetically twinned pyroxene (fig. 10). For some unexplained reason, these rarely grade into the half glassy porphyritic forms, the entire chondrule consist-

FIG. 10

ing of the closely crowded pyroxenes with comparatively little, if any, interstitial glass. In figure 11, from the Parnallee stone, it will be noted the crystals are in some instances slightly curved, their vertical axes lying approximately parallel with the circumference of the circle

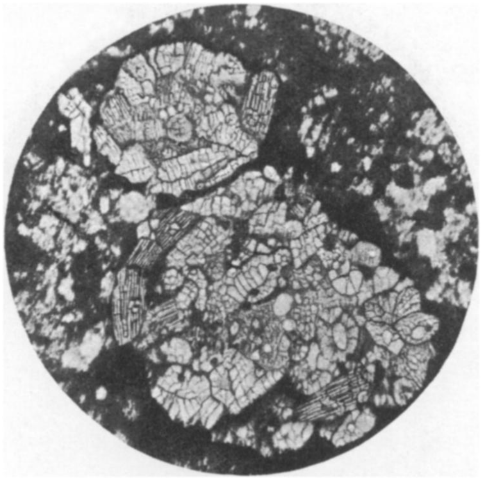

FIG. 11

which forms the border of the section. The appearance is as if the chondrules had been molded by external forces after the crystals had formed but while yet in a more or less plastic condition. Again, the pyroxene crystals abut sharply against the border and are cut off at the margin as

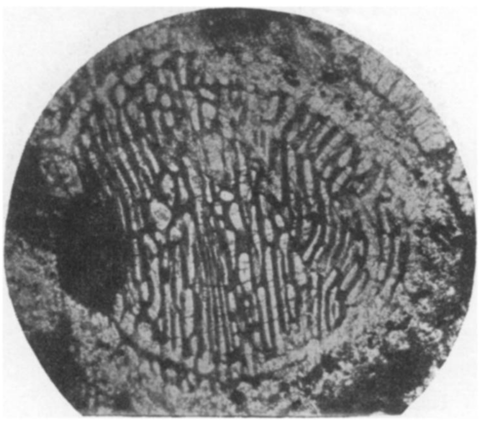

FIG. 12

in the half glassy, porphyritic forms mentioned above, and as shown in figures 10 and 11. Occasional forms are met with which have all the appearance of fragments, slightly rounded, of holocrystalline granular rocks, which as noted later, I believe them to be.

IV. *Secondary Borders about Chondrules.*—A not uncommon feature of the chondrule is the narrow border or rind about the circumference. These borders as a rule, are of lighter color than the interior, of a clear, more pellucid nature, though it may be including portions of the minerals characteristic of the matrix in which they are embedded. This is well shown in the olivine chondrule, figure 12. This border has an appearance at once suggestive of the secondary intergrowth or enlargement often seen in feldspars and other minerals of terrestrial rocks. The later portions sometimes, though not always, have the same optical orientation as the interior. I am not certain if this border is of a like nature to that described by Tschermak about some of the chondrules of the Grosnaja stone and which he considered of secondary origin. In some instances

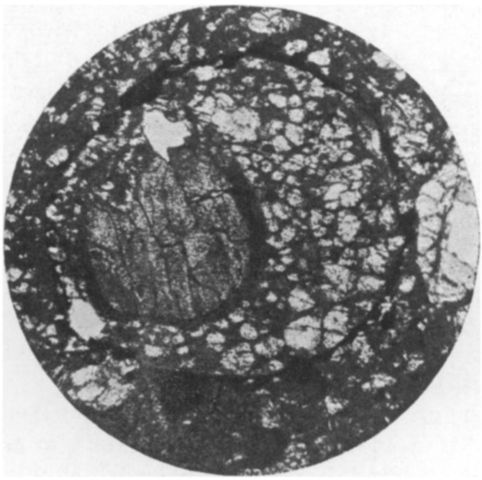

FIG. 13

the chondrules are surrounded by an irregular border of metal or metallic sulphide.

V. *Double or Compound Chondrules.*—Occasional forms are met with in which a large crystal of olivine or pyroxene is inclosed by a border of finer crystals of the same mineral but suggestive of a later generation. More common are forms such as are shown in figure 13. The crystals are of enstatite but the larger one is filled with minute cavities which are lacking in the smaller forms. Of greater interest is the occasional occurrence of a chondrule within the mass of a second or larger form, as figured by Tschermak, on plate 8, figure 1, of his *Beschaffenheit.* I will refer to this also, later.

The descriptions thus far given are of the most perfectly formed and outlined chondrules only. The broken, angular and, in some cases, distorted radiate enstatite forms are plainly mechanical derivatives, and while they have a bearing upon the origin of the masses in which they occur,

they can, except as noted below, have little bearing upon the subject of the origin of the chondrules themselves. They are, therefore, passed over for the present.

THE ORIGIN OF THE CHONDRULE

I. *Theories of Origin.*—In this review it will perhaps not be necessary to go back much beyond the time of the introduction of the microscope and thin sections into the study of rock structures since obviously little that was accurate could be told of them by the naked eye alone.

A brief glance at the literature is sufficient to suggest that many of the opinions expressed have been based upon examinations of but a limited number of occurrences which quite failed to yield the information necessary for building satisfactory hypotheses or conclusions.

Reichenbach, as early as 1860[7] wrote, "Aus allerdem wird es klar, das die Einschlusse in den Meteoriten, als die Trümmer und die geschicbartigen Knollen und Kugeln darin, keine einfach nachen Bestantheile, sondern nichte anderes sind als auch wie die Meteoriten. Meteoriten nur von anderer Anordung ein und derselben naturn Bestandtheile" And again, "Es sind also die Einschlusse theils kleine meteoriten, theils Trümmer von meteoriten von hohenen Alter als diejenigen meteoriten es sind, in welche sie eingeschlossen vorkommen; es sind altere kleinere meteoriten in jungerern grossern meteoriten." In brief, and in plain English, he believed each particle as now found to represent a minute but independent meteorite derived from the breaking up of some older preëxisting stone and now included as a constituent part of one new formed.

In discussing the microscopic structure of meteoric stones, H. C. Sorby, in 1864, wrote,[8] "It would, therefore, appear that, after the material of the meteorites was melted, a considerable portion was broken up into small fragments subsequently collected together, and more or less consolidated by mechanical and chemical action. * * * Apparently this breaking up occurred in some cases when the melted matter had become crystalline, but in others the form of the particles lead me to conclude that it was broken up into detached globules while still melted. This seems to have been the origin of some of the round grains met with in meteorites; for they occasionally still contain a considerable amount of glass, and the crystals which have been found in it are arranged in groups radiating from one or more points on the external surface in such a manner as to indicate that they were developed after the fragments had acquired their present spheroidal shape." In continuation of this same idea in 1877,[9] Sorby wrote: "As is well known, glassy particles are sometimes given off from terrestrial volcanoes, but on entering the atmosphere they are immediately solidified and remain as mere fibres, like *Pele's hair*, or as more or less irregular laminae, like pumice dust. The nearest approach to the globules in meteorites is met with in some artificial products. By directing a

strong blast of hot air or steam into melted glassy furnace slag, it is blown into spray, and usually gives rise to pear-shaped globules, each having a long, hair-like tail, which is formed because the surrounding air is too cold to retain the slag in a state of perfect fluidity. Very often the fibres are of the chief product. I have never observed any such fibres in meteorites. The formation of such alone could not apparently occur unless the spray were blown into an atmosphere heated up to near the point of fusion, so that the glass might remain fluid until collected into globules. The retention of a true vitreous condition in such fused stony material would depend on both the chemical composition and the rate of cooling, and its permanent retention would in any case be impossible if the original glassy globule were afterwards kept for a long time at a temperature somewhat under that of fusion. The combination of all these conditions may very well be looked upon as unusual, and we may thus explain why grains containing the glass are comparatively very rare; but though rare they point out what was the origin of many others. In by far the greater number of cases the general basis has been completely divitrified, and the larger crystals are surrounded by a fine-grained stony mass. Other grains occur with a fan-shaped arrangement of crystalline needles, which an uncautious, non-microscopical observer might confound with simple concretions. They have, however, a structure entirely different from any concretions met with in terrestrial rocks, as for example that of oolitic grains. In them we often see a well-marked nucleus, on which radiating crystals have been deposited equally on all sides, and the external form is manifestly due to the growth of these crystals. On the contrary the grains in meteorites now under consideration have an external form *independent of the crystals* which do not radiate from the centre, but from one or more places on the surface. They have, indeed, a structure absolutely identical with that of some artificial blowpipe beads which become crystalline on cooling. With a little care these can be made to crystallize from one point, and then the crystals shoot out from that point in a fan-shaped bundle, until the whole bead is altered. In this case we clearly see that the form of the bead was due to fusion, and existed prior to the formation of the crystals. The general structure of both of these and the previously described spherical grains also show that their rounded shape was not due to mechanical wearing. Moreover, melted globules with well-defined outline could not be formed in a mass of rock pressing against them on all sides, and I, therefore, argue that some at least of the constituent particles of meteorites were originally detached glassy globules, like drops of fiery rain." In this Sorby would appear to have had reference only to *kugels* with radiate, internal structure.

Tschermak, who together with Haidinger, was one of the first to pronounce on the tuff-like character of the chondritic meteorites, announced in 1874[10] the opinion that the individual chondrules (kugelchen) were but

rock particles which became simply rounded under conditions similar to such as might exist in the throat of a terrestrial volcano. "Ich widerhole hier nur das Eine, dass Ich die Chondrite fur Zerreibungs-Tufe, und die Kugelchen derselben fur solche Gesteinspartikelchen hatte, welche wegen ihrer Zähigkeit bei Zerreiben des Gesteines nicht in Splitter Aufgelöst, sondern, abgerundet wurden." And again in 1875[11], "Man kann sich allenfalls vorstellen das die Steinmassen, welche der Zerreibung ausgesitz weren, ziemlich weich gewesen sein und würde sich dadurch der Vorstellung Daubrees nähern, welcher an ein Gestein denkt welches in einer Gas masse wirbelnd erstarrte; doch is es sicher, das die Kugelchen das Resultat einer Zerreibung sind." In both of these quoted expressions Tschermak seems to have had in mind only the granular and porphyritic polysomatic forms, and the fragmental "kugelchen."

Three years later[12] after a consideration of the depressions and excrescences occurring in and on the chondrules of the Tieschitz meteorite, he came to a partial agreement with Sorby conceiving that "Die Kügelchen sind nach wie vor wegen der tuffartigen Beschaffenheit der Meteorsteine als Resultate volcanischer Eruptionen und Explosionen anzusehen, aber ihre Form dürfte doch eher von einem plastischen Zustande, als von der Zerreibung starrer Partikel abzuleiten sein." And again, after another four years[13] he announced, "Ich hatte * * * zu der Ansicht gefuhrt wurde, dass die Kügelchen der chondrite als erstarrte Tropfen anzusehen sind, während die aus Splittern bestehende Grundmasse nach wie vor als vulkanischer Detritus zu betrachten wären."

Daubree[14] seems also to have held the opinion that the majority of chondrules were simply debris particles rounded by attrition. "J'ai montre," he wrote, "que la structure globulare telle qu'elle se presente dans certains types * * * a ete imitee artificiallement, et s'explique par une sort de granulation, aperee au moment ou la substance se solidifie. Mais le plu souvent, les globules des meteorites parraissent etre des simples debris arrondis par frattiment."

F. Rinne[15] by means of a simple electric device was able to fuse the silicate constituents of meteorites and by abrupt alterations of the strength of the current produce a "spratzen" of the melt resulting in the projection from the crucible of small drops which quickly cooled in the form of "kugels." To some such action he would ascribe the formation of meteoric chondrules. Later, by the aid of an oxygen blast and a Linnemann burner he was able to produce enstatite beads evidently in every way comparable with meteoric chondrules.[16] These it will be observed are really synthetic demonstrations of the possible correctness of Sorby's views. Berwerth in 1901[17] announced his conviction that the chondritic stones were tuffs more or less completely metamorphosed by heat, and seemed to regard the individual chondrules as portions of the melt that cooled in globular form. Borgström[18] in his description of the Hvittis

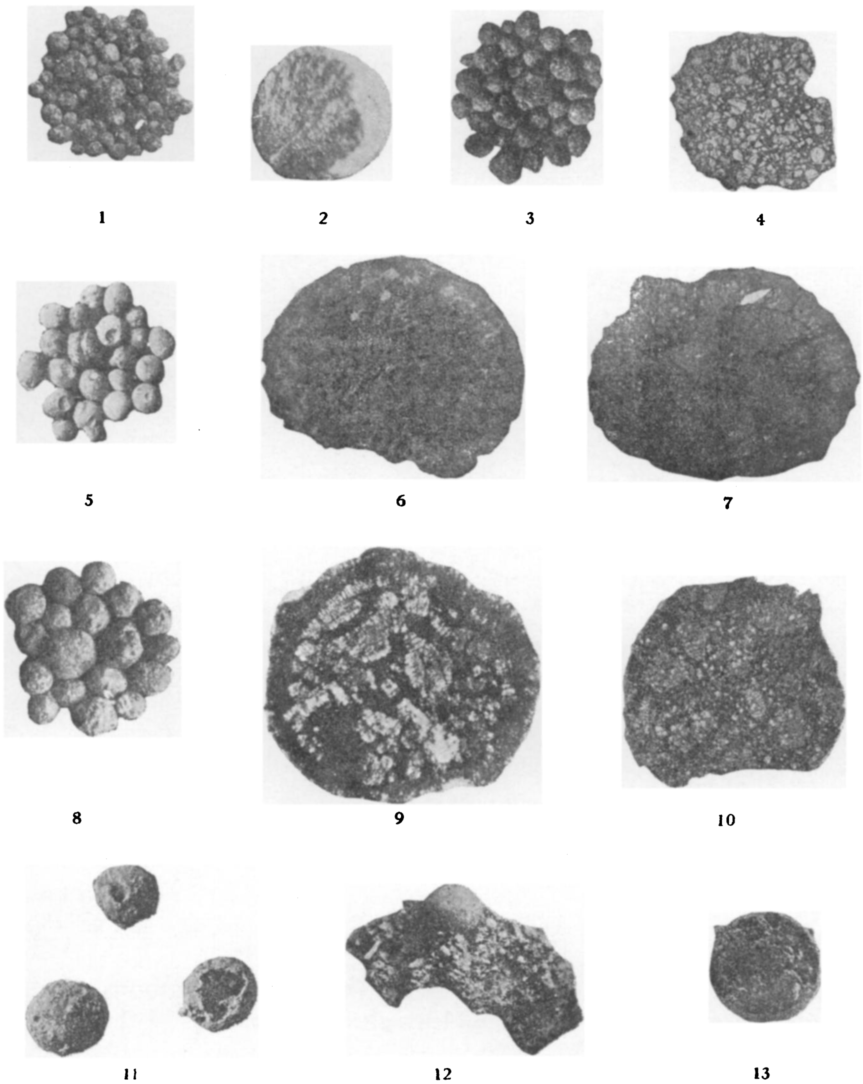

PLATE 1

Fig. 1.—Cluster of smooth chondrules out of Allegan stone.
Fig. 2.—One of the same chondrules broken and showing radial structure.
Fig. 3.—Cluster of rough chondrules out of Allegan stone.
Fig. 4.—Thin section of one of same.
Fig. 5.—Cluster of smooth chondrules out of Bjurböle stone.
Figs. 6 and 7.—Thin sections of same.
Fig. 8.—Cluster of rough chondrules out of Bjurböle stone.
Figs. 9 and 10.—Thin sections of same.
Figs. 11–13.—Chondrule-like bodies from Bessemer convertor, Sparrow Point, Md., Steel Works.

stone (1903) (a crystalline chondrite), states that the chondrules are always so firmly intergrown with the ground that it is often impossible to determine where the one leaves off and the other begins. In many instances, the enstatites of a chondrule extend out into the ground mass with which they are intergrown. As noted, the Hvittis stone is a crystalline chondrite; this might suggest either a crystallization of the chondrule *in situ* or a case of secondary enlargement. In writing of the Shelburn stone, a grey chondrite, however, he says,[19] "Each individual chondrule represents a structure of cooling and crystallization from a molten state, and as their structure shows an intimate relation to the boundary of the chondrule it must be supposed that each, at the time of its solidification, was a separate unit. Because chondrules of the same chemical composition have a different structure, they must have been formed under different

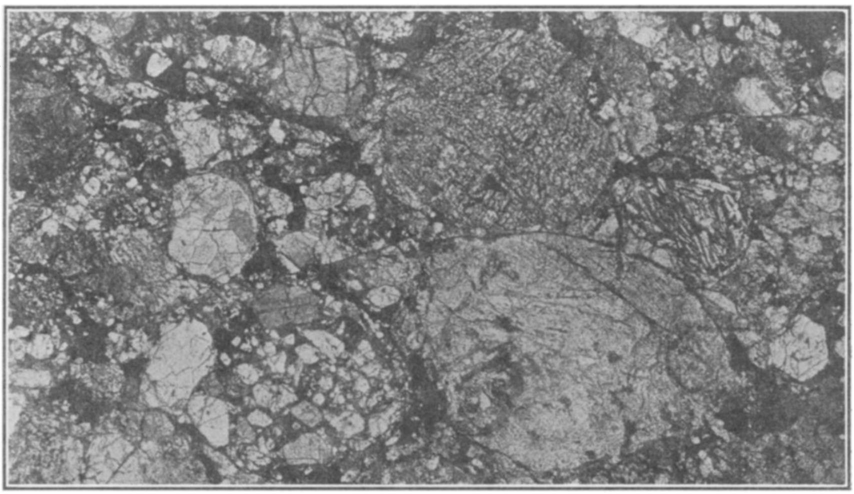

FIG. 14

physical conditions. Since such a variety of conditions cannot have existed in the narrow space in which the different structures now are met with, the chondrules must have accumulated after solidification." Such a condition is well shown in figure 14, from the stone of Cedar, Texas. Meunier[20] basing an opinion apparently upon the theoretic work of M. Faye suggests the probability of the chondrules resulting from the sudden condensation of a cyclonic vapor. "Il parait difficile de ne pas admettre que les chondres sont aux roches de precipitation gazeuse ce que les dragees de Carlsbad et le fer en grains sont aux roches de precipitant aqueus * * * Conformement a la terminologie dont font usage les paleontologistes a propos du vent fossiles du soleil fossile, de la pluie fossile, on serait tente de les qualifier de *cyclones photospherique fossiles*." This is conceivable, to the present writer, only in the case of radiate enstatite or monosomatic forms.

Brezina, to whom is so largely due the building up of the magnificient collection at Vienna, concludes a review[21] of the subject with the statement, "Durch die vorangefuhrten Beobachtungen können wohl die alteren Ausschauugsweisen als beseigtig betrachteh werden, und wir können wohl mit Bestimmtheit die Meteoriten als gestörge über hastete Krystallbildungen in einem einzigen gemengten magma bezeichen." This I understand includes both the ground mass and its chondrules.

Hussak, basing an opinion on experimental work by himself and Dolter[22] suggests that chondritic meteorites, like that of Uberaba, Brazil (a crystalline chondrite), originate through the long continued immersion of meteoric stones in a nickel-iron-rich magma, and are to be regarded as true volcanic ejectamenta, "Ich möchte demnach die Meteorsteine durch ultrabasische Eruptivgesteine vergleichen und die Bildung der Chondren wie der Trümmerstrutur und der schwarzen Adern als eine magmatische Eirnwirkung vor der Ejektion ansehen. Daher die vollstandigen Ubergange in Siderite und die Deutlichen Korrosionserscheinungen an den grossen Olivinkristallen der Pallasite."

C. Klein, in 1906,[23] evidently basing an opinion largely on figures of chondrules in the works of Hahn and Tschermak, affirmed that there occur many ideally perfect forms that lack the eccentric radiating structure, but are "radial strahlig," from a centre, equally in all directions and are *true spherulites*. Those not having this perfection of structure are considered fragments. It may be well to note before going further, that Klein apparently stands alone in holding these views though they may be correct for certain forms.

Wahl[24] would explain the formation of the chondrule as due to the cooling of a silicate melt in a heated atmosphere, the resultant drop crystallizing from the surface inward. "Die Entstehung der Chondren lässt sich also ganz allemein als durch Zerstäubung von Silikatschmelz fluss innerhalb einer heissen Atmosphäre und Kristallization der hierdurch enstandenen Tropfen von aussen nach innen zu erklaren." This again would seem to refer only to the cryptocrystalline, radiating enstatite, and the barred and monosomatic olivine chondrules.

Finally, in 1913, Fermor,[25] of the Indian Survey, suggested that the chondrules are remelted garnets.

In my preliminary considerations of this subject, I felt that in order to arrive at a solution of the problem it would be necessary to begin with a study of the crystalline chondrites, since in case the chondrules were spherulites, it would be here that they would be found in their primary condition of development. A study of all the thin sections of stones belonging to this group, now in the Museum collections has, however, brought about a change of view since in none of them do I find chondrules developed in the variety and perfection of forms existing in those meteorites which are plainly tuffaceous. This fact and others to be mentioned later have

led me to regard the larger part if not all chondritic stones as originally tuffaceous and owing their more or less crystalline condition, where such exists, to heat and pressure in a nonoxidizing or even reducing atmosphere. The study of the origin of the chondritic meteorites must begin then with the study of the chondrules themselves as found in the tuffs and a gradual tracing of them back through the crystalline "kugelchen" forms to the holocrystalline types.

Disregarding the fragmental, angular and more or less splintered radiate forms concerning the fracturing and secondary origin of which there can be no doubt, and confining ourselves to those which so far as can be determined have the form and structure assumed at the time of their formation and are of a more nearly perfect spherical, oval or "kugelchen" shape, their study in thin section brings out very clearly two important fundamental distinctions. 1st. The most perfectly spherical and oval forms, sharply differentiated from the matrix, are those showing a cryptocrystalline or radiating internal structure, and are mineralogically of pyroxene (enstatite or bronzite). These forms often show excrescences or saucer-shaped depressions, as through shrinkage or interference during solidification. 2nd. Those of a polysomatic nature, composed of phenocrysts of olivine or pyroxene in a more or less glassy base, or of an almost holocrystalline aggregate of one or more minerals, are of irregular outline, have more the appearance of fragments and never show the saucer-shaped depressions and excrescences. Further than this, it becomes very quickly evident that a theory of origin which will account for the first, must fail in the case of the second. It is not possible for instance, that a chondrule of phenocrysts in a glass base like that shown in figure 8, should have originated under the same conditions and in the same manner as that in figure 3.

It is possible to conceive of a basic magma containing the necessary constituents for the formation of olivine or enstatite to be in a sufficiently liquid condition to cause, or allow it, when thrown into a hot or thin atmosphere, to take the form of spherical drops which on cooling will become glassy or crystalline, according to conditions. Should the drop begin cooling on one point of its surface, the crystals might radiate from this point outward, or rather inward with reference to the chondrule, giving rise to the radiated form like those of the Elm Creek and Parnallee stones (figs. 3 and 5). In case the cooling began at several points on the surface, the interior of the chondrule would be broken into areas each of which represents an independent crystallization, as shown in figure 15. It would thus be fairly easy to account for the monosomatic glassy, cryptocrystalline and radiate forms[26] (Kugels), and even the barred forms so characteristic of olivine chondrules in the stones of Hendersonville and Tennasilm.

The porphyritic polysomatic forms composed of phenocrysts of pyroxene

or olivine in a glass base like those of Tennasilm (fig. 8), or Cabarrus (Monroe) offer, as it seems to me, insuperable difficulties to any such theory of origin and I am unable to agree with Dr. Wahl in his, at first

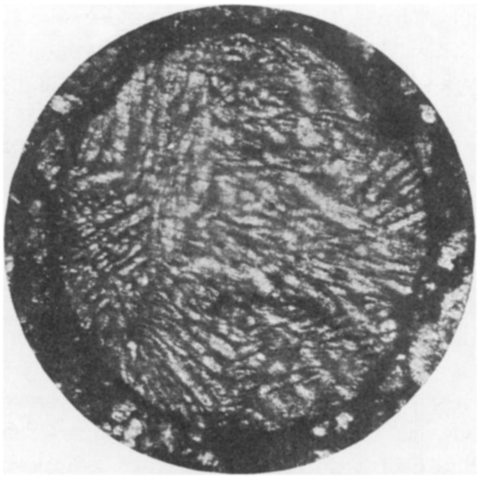

FIG. 15

thought, lucid and satisfactory explanation. It is obviously impossible that such could have originated from the cooling from the surface inward of a molten drop. Even in the hot air of Dr. Wahl's imagination the crys-

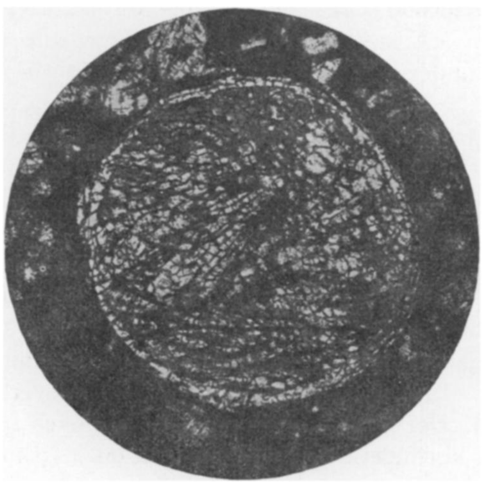

FIG. 16

tallization must almost certainly have begun at the surface and progressed inward giving rise to an exterior crust or border as in figure 16. This seems almost too self-evident to need mention. One must consider such

(i. e., the porphyritic forms) in the light of knowledge gained from a study of terrestrial rocks, and as due to the gradual cooling of a melt of some considerable proportions to the point of crystallization of the phenocrysts, followed by an abrupt refrigeration resulting in the production of the glassy base. This crystallization and final cooling can scarcely have taken place after the drop or chondrule took on its present form. It would seem doubtful, also, if a melt which had cooled sufficiently to allow the formation of the phenocrysts would be sufficiently fluid to permit the formation of the spherical drops under any probable conditions. It is true the separating out of the crystals would leave a magma more fusible than was the original, but it would still require an almost impossible condition to bring about a formation of the pellets as suggested.

It is questionable further if conditions could have been such as to bring about a practically instantaneous, or rather simultaneous cooling throughout the entire chondrule. If cooling as an isolated drop of molten matter in which were floating the phenocrysts there would seemingly, almost for a certainty, be occasional indications of an earlier cooling on the outer surface manifested by the formation of the crust as already mentioned, or conditions of strain or, possibly, signs of incipient crystallization. Such I do not find, the glass being uniform in physical properties and apparently in composition from centre to circumference of the chondrule as it appears in the section. The same holds true of chondrules which are nearly or quite holocrystalline, like those of twinned pyroxene figured[27] by Tschermak from the Renazzo stone, or those from the Cullison, Kansas, stone described by myself.[28] In these cases one has to consider a much more uniform and gradual reduction of temperatures, such as would give the crystallographic forces full opportunity to perform their task. But were the material in the form of an isolated drop, and the forces given sufficient time the exterior form of the aggregate can scarcely be conceived as smoothly spherical, but must have been irregular with numerous projecting angles such as are frequently to be seen in spherical concretions of pyrite and marcasite. Such forms I do not find though I have sought for them diligently. In forms like figures 8, 9 and 10, it is, I think, self-evident that the original surface has been reduced by attrition, and whatever character it may have had has been lost. This same probability of reduction in size is suggested by the twinned pyroxene chondrules in the Parnallee stone. It is obvious that such cannot have resulted from the cooling and crystallization of a molten drop unless it were one of considerable greater magnitude. The occasional curved-enwrapping character of the outer crystals (fig. 11) can only be accounted for on the supposition of Tschermak and Daubree, already noted, that the material was somewhat soft and plastic.

It is notable further, so far as my own observation goes and so far as

I can learn from the descriptions given by other writers, that the peculiar saucer-shaped depressions (fig. 4, p. 452 and fig. 5, pl. 1) which were surely formed at the time of solidification are limited to the cryptocrystalline and radiated enstatite types. They are never found in the polysomatic, porphyritic and holocrystalline forms although these may be of like mineral composition. The cause of this cannot then be chemical. It would seem fair to assume that it was fundamental and due to their origin under quite different conditions.

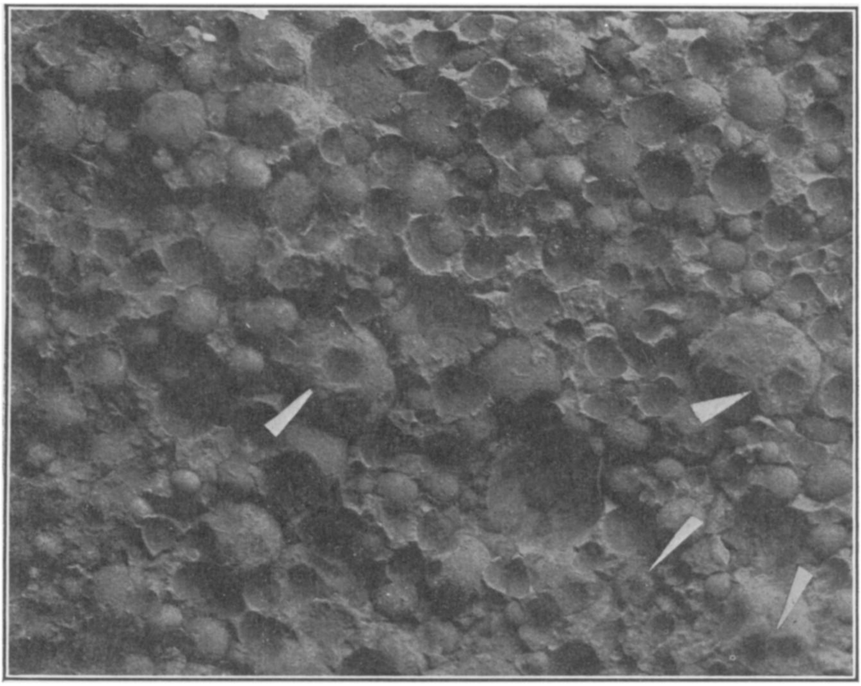

FIG. 17

Chondrule-like blebs of metallic iron in furnace slag showing, in some instances, depressions similar to those of the enstatite chondrules in meteorites. The white pointers mark some of the more prominent forms.

Concerning the origin of these depressions and indeed as bearing upon the general subject of chondritic formation, it may be well to add incidentally that in a fragment of furnace slag received from Lawrence County, Tennessee (exact locality unknown), I find abundant beautifully spherulitic chondrules of metallic iron embedded in the glassy slag. These are from one to three mm. in diameter and often so densely crowded as to have mutually interferred so that when separated there is left on one of them a concavity similar to that of the enstatite chondrules. Indeed the simulation of exterior form is almost perfect (see fig. 17). If, however

one were to assume that the mode of formation of the concavity was the same in the two cases it will apparently be necessary to further assume that the chondritic forms, the fused drops of "fiery rain," accumulated in such quantities before all were fully indurated as by their weight to allow those most firm to indent those still plastic. Were it not for the rarity of the double or excrescent bearing forms referred to elsewhere, it might be suggested that the concavities were due to the breaking apart, one from another, after solidification. It should be added that I have not yet found any evidence even suggesting that the enstatite kugels with radiate structure are basic segregations out of a more acid magma as are the metallic forms out of the slag, nor indeed, to indicate that they result from the disintegration of previously solidified magmas of any kind.

II. With these facts in mind it seemed advisable to study the isolated chondrule, freed from its matrix. For this purpose the loose textured Allegan and Bjurböle stones, of pronounced tuffaceous type, afforded most excellent material, both in quality and quantity. From the disintegrated Allegan stone there were picked out a considerable series of the rounded granules such as are ordinarily classed as chondrules. These, under a hand lens, it was found, could be readily divided into two classes. First, those of regular spherical or oval form with comparatively smooth though lusterless surfaces, usually with one or more depressions as in figure 1, pl. 1, and sometimes with deeper pittings. These were of a light green color, in a few instances, but mainly dark, nearly black. When broken, such show a straight smooth fracture and distinct eccentric radial internal structure (fig. 2, pl. 1). Of a number of thin sections made none showed a holocrystalline or porphyritic structure. Some were so finely cryptocrystalline that it was only by analogy that they were determined as pyroxenic. Others were distinctly eccentric radiating, the bars possessing sufficient crystalline development to make it possible to determine their orthorhombic pyroxenic nature.

Second, the second series was composed of rounded and irregular granules with rougher surfaces, lacking the shell-like rind or casing of the first (Fig. 3, pl. 1). They were hard, undergoing no further disintegration under ordinary friction, sometimes quite spherical, but grading into angular fragments with angles blunted or rounded and with an uneven fracture. Sections of these showed a quite different structure from the first mentioned. Some were wholly crystalline, granular or of short radiating enstatites, while others were beautifully porphyritic consisting of olivine or pyroxene in a glass base. The porphyritic marginal crystals showed plainly that the present form of the granule was due to mechanical attrition (fig. 4, pl. 1). These forms are undoubtedly the ones that in the thin section give the forms shown in figures 8, p. 454, and 10 on p. 455. There can be no question but what they owe their present form and dimensions to attrition as suggested by Tschermak, though whether the

original forms were spheroidal or that of an ordinary angular fragment there is no absolute means of determining. From the examination of a large number of cases, I am inclined to the belief that these last are altogether of fragmental origin, broken fragments rounded by mechanical action.

From a lot of disintegrated Bjurböle material, generously furnished by Dr. J. J. Sederholm, there were in like manner picked out the two series shown in figures 5 and 8, pl. 1. It will be noted here that there is a greater contrast between the two forms than in the case of Allegan. Those in figure 5 are typical blebs of fiery rain, smooth, with a rind-like coating showing frequent depressions and more rarely excrescences. A large number of like forms were broken with a hammer and yielded smooth, cleavage-like fractures in part with a radiate structure. In thin sections all showed either a dense cryptocrystalline or radiate internal structure (figs. 6 and 7).

The forms shown in figure 8 were, as in the case of Allegan also, less symmetrically oval or spherical, rough exteriorly, never encrusted or showing depressions or excrescences.[29] On breaking with a hammer some of these yielded a smooth, straight, cleavage-like fracture and in the section showed a radiate structure; others and the larger part showed an uneven fracture and in the section were irregularly granular, glassy and porphyritic (figs. 9 and 10).

I find a similar, though not always so plainly marked, distinction in the chondrules separated out from the meteorites of Ochansk, San Emigdio and Soko Banjo. A further study of a large number of sections of chondritic stones fully confirms these observations. Stated in brief the conditions and conclusions are as follows:

(1) Only the chondrules of glass and cryptocrystalline or radiating enstatites (kugelchen) present the rounded or oval form with smooth rind-like crust and surfaces, with often one or more saucer-like depressions or excrescences such as are consistent with a theory of origin as fused drops of "fiery rain" (Sorby).

(2) Chondrules of a compound, holocrystalline nature, and those porphyritic through the development of olivine or pyroxene phenocrysts in a more or less glassy base are lacking in smooth exteriors and though often quite spherical in outline, are as a rule more or less irregular and in many instances show unmistakable evidences of an origin of form through mechanical attrition. These distinctions are well shown in figures 3 and 5, and in the general view from a thin section of the stone of Cedar, Texas (p. 462).

Many of the irregular forms, it is true, are found to be of the radiating or cryptocrystalline enstatite. This is evident from an examination of

the thin sections and has also been found to be the case in some of the forms freed from the matrix. They are plainly fragments of the encrusted forms and need no explanation. In no case, however, have I found a part glassy and porphyritic or holocrystalline structure developed in a polysomatic chondrule which does not suggest, from an examination of its external form, an origin as a rock fragment rather than a molten drop.

That all the forms described cannot be attributable to a common origin, I consider self-evident, as already noted. The objections to an acceptance of the "fiery rain," or "fused drop" hypothesis in accounting for these last forms may be concisely stated as follows:

(1) They are irregular in outline.

(2) They never show the smooth, rind-like surfaces so characteristic of the enstatite kugels.

(3) The outlines are not those of the original body from which they were derived, but for the most part plainly due to abrasion.

(4) They show no gradations in crystallization from border to center.

(5) They never show the peculiar surface depressions so characteristic of the enstatite radial and cryptocrystalline forms.

(6) In brief, their present structural peculiarities, both external and internal are entirely inconsistent with any conceivable theory of origin but that of detrital particles from solidified magmas.

It is perhaps questionable if such forms should be considered true chondrules and perhaps the term pseudochondrule or *chondroid* had best be applied to them.[30] The true chondrules are those of the spherulitic or *kugel* type; others are rock fragments reduced to their present form through mechanical attrition.

As bearing still further upon the question attention may be called to somewhat similar forms of known and artificial origin. In figures 11 to 13, pl. 1, are chondrule-like forms found among the iron furnace slags at the Sparrow Point, Md., works of the Bethlehem Steel Co. Such are certainly strongly suggestive, in form, to meteoric chondrules though it is to be remarked that they are, interiorly, vesicular, almost pumiceous. Like forms I have found being blown from the Bessemer converters in the more energetic periods of operation. They formed true drops of "fiery rain." In figure 12 is shown one of these imbedded in the scoriaceous slag. Qualitative tests show these to consist largely of silica and oxides of iron, a little lime, and included minute flecks of metallic iron.

In the above discussion, the fact has not been overlooked that very many of the glass and enstatite chondrules relegated above to the fiery rain hypothesis have likewise suffered abrasion through external agencies. This is plainly evident from the figures given and the multitude of fragmental forms found in many chondritic stones. The encrusted form of

so large a number of chondrules of this type and the complete absence of such crust on the porphyritic and holocrystalline forms I have just been discussing are in themselves sufficient to enable one to safely differentiate between the two.

The conclusions here reached are not quite so sweeping as those reached by Merrick in his humorous poem on the changeable colors of the chameleon, where he announces that "All are right, and all are wrong," but as is so frequently the case it seems to show that two or more of the opinions advanced were essentially correct and their apparent differences due to failure to recognize all of the facts I have here presented, and that of the many varietal forms of chondrules not all may have a similar origin.

Before leaving this section of the subject, it may be well, however, to present reasons for the non-acceptance of certain of the views presented and enumerated. It will be noted that the conclusions I have reached, bear out for the varying types the ideas of both Sorby and Tschermak, those of the first mentioned supported by the experimental work of Rinne. With the views of Borgström and of Ramsay, so far as they bear upon the subject in the papers quoted, I am in agreement. With those of Hussak, so far as relates to the production of chondritic structures through the corrosive action of a nickel-iron-rich magma, I find no confirmation. Not only is there little evidence that such a magma would corrode the silicates, but as in the case of meteorites of Brezina's Röckiky group (Admire and Eagle Station) there is direct evidence that it would not. Further than this, there is evidence that in my own opinion, tends to show that the iron of meteorites is altogether secondary and due to a reduction of some easily reducible compound like lawrencite, as I have elsewhere frequently stated.[31] The expressed conclusions of Berwerth and Wahl are not sufficiently detailed to admit of close comparison other than to say that they both seem applicable to the chondrules of the encrusted enstatite (kugel) type first mentioned, but not to the holocrystalline and porphyritic forms. With reference to Dufrenoy's comparison of this structure to perlitic glass[32] it can only be said that while at first thought it might seem applicable to the glassy and half glassy porphyritic types, I find nothing whatever to sustain it and several facts which militate against it. First there are in no instances indications of perlitic cracks and second, in the terrestrial perlites, so far as my own observation goes, the cracks always pass around any existing phenocrysts, rather than through them as they must to have produced the forms shown in figure 8. It may be added that perlitic structure in terrestrial rocks is regarded as due to shrinkage and limited to acidic magmas containing a considerable quantity of moisture. The structure is quite unknown in rocks as basic as are the meteorites.

With reference to the spherulitic nature of the chondrules as advocated

by Klein, I can only say that I find no evidence, with a single possible exception, satisfactory to me, to bear out the idea. This exception occurs in the stone of Barratta, Australia, in one slide of which I find the spherulitic bodies shown in figure 1, p. 451. These are as sharply outlined and as easily detached from the matrix as any spherulites and so closely resemble the true spherulite from one of the acid glasses as on casual inspection to strongly suggest their similar nature. Indeed, I have thus far failed to find evidence to completely satisfy me that such would not be so classed. It is to be noted, however, that between crossed nicols these break up each into several more or less well-defined areas showing an illy defined structure and over each of which the dark cloud sweeps irregularly as the stage is revolved. They lack the definite radial structure of typical spherulites and never between crossed nicols show the black cross, though how much reliance can be placed upon this distinction, I am not prepared to say. They are sufficiently distinct from the other chondrules in the stone to suggest an entirely different mineralogical nature, but the amount of material at my disposal is not sufficient to allow a determination. Liversidge,[33] in his description, makes no mention of these peculiar forms.

Finally with reference to Fermor's fused garnet theory it may be stated that in no case have garnets been proven to actually occur in meteorites, and further, did the chondrules so originate it would be a perfectly safe assumption that we should sometime and somewhere find residual traces. So far as my observation goes, no such cases are on record.

[1] Published by permission of the Secretary of the Smithsonian Institution. This paper is supplementary to the author's work on "Minor Constituents of Meteorites" made under a Grant from the J. Lawrence Smith Fund of the National Academy of Sciences (see Memoirs of the Academy, **14,** 1916, pp. 1–29; 1919, pp. 1–15; and these Proceedings, March and June 1915, April 1918, and January 1919).

[2] Geschreibung u. Eintheilung der Meteoriten, etc., *Abhand. d. K. Akad. Wiss. Berlin,* 1863.

[3] See Farrington, *Meteorites,* p. 200.

[4] Or "globular," see *Proc. Amer. Phil. Soc.,* **43,** 1904 (238).

[5] See particularly *Die Mikroscopische Beschaffenheit der Meteoriten,* and *Meteoritenkunde,* respectively.

[6] No attempt in these studies has been made to distinguish between enstatite and the ferruginous variety bronzite.

[7] *Pogg. Ann.,* **111,** p. 384.

[8] *Proc. Royal Soc.,* June 1864.

[9] *Nature, London,* April 5, 1877 (296).

[10] Die Trümmerstructur d. meteoriten, etc., *Sitz. k. Acad. Wiss., Wien,* **70,** 1874 (4).

[11] *Ibid.,* **71,** 1875.

[12] *Denk. Math. Natur. Classe kaiser. Akad Wiss,* **39,** 1878.

[13] *Sitz. k. k. Akad. Wiss., Wien,* **95,** 1882 (205).

[14] *Geologie Experimentale,* 1879 (530).

[15] *Neues Jahrbuch Min. Pet.*, **2,** 1895 (229–246).

[16] *Ibid.*, —, 1897 (259–61).

[17] *Centralblatt Min.*, etc., No. 21, pp. 641–47.

[18] Die Meteoriten von Hvittis u. Marjalatti, Helsingfors, 1903.

[19] *Trans. Royal Astr. Soc., Canada*, 1904.

[20] *C. R. Paris Acad. Sci.*, **96,** 1883 (868).

[21] *Die Meteoriten in Sammlungen*, etc., 1885.

[22] *N. Jahrb. Min.*, etc., **I,** 1884 (18–43). They immersed fragments of an "olivine-fels" for many hours in a slowly cooling melt of nephelin basalt. The stone was strongly attacked and the outer portions, in close contact with the melt, shattered and corroded, the olivine granules becoming filled with embayments and enclosures of a secondary colorless glass, all strongly suggestive of meteoric chondrules.

[23] *Studien uber Meteoriten*, p. 35.

[24] *Zs. Anorg. Chem.*, **69,** 1910 (52–96).

[25] *Records Geol. Survey India*, **43,** 1913 (45).

[26] Such forms may readily be artificially reproduced by fusing to a bead some readily fusible mineral like stibnite. Although unfortunately opaque the radiate structure may be plainly seen on a broken surface of the globule.

[27] *Mikro. Beschaff, der Meteoriten*, plate 15.

[28] *Proc. U. S. Nat. Mus., Washington*, **44,** 1913 (326).

[29] Borgström and Ramsay in their description of the Bjurböle stone (*Bull.* No. **12,** *Com. Geologique Finland*) mention the irregularity in form of the chondrules, as seen in thin sections. They say, p. 18 under (6) *Polysomatische Olivinchondren mit Nickel eisen* "Die Chondren dieser Art haben selten regelmässig runde Form." and again, on p. 19 under (8) *Chondren aus Glas mit wohlbegrenzten dicken Olivinen*, "Sehr selten besitzen die Chondren von Typus (8) regelmassige rundliche Begrenzung, sondernerscheinen in den meisten Fallen mit Zufalligen eckigen oder buckligen Formen."

[30] In figure 1, of plate 8, of his *Mikroskopische Beschaffenheit*, Tschermak shows a small monosomatic chondrule inclosed in a larger porphyritic form of the same mineralogical composition, from the stone of Dhurmsala. It is to be noted, however, that while the smaller monosomatic form is evidently the direct product of a cooling molten magma, it has no necessary connection with the ground in which it is embedded and there is nothing in the appearance of the larger form, so far as can be judged from the figure, to indicate that it is not merely a rounded fragment of some pre-existing chondritic stone. This explanation will not, however, hold good for the double chondrule in the Borkut stone shown in figure 2 of his plate 19. In the case of our figure 3, plate 3, from the Okechobee stone there can be no question but that the chondrule is merely a fragment inclosing a large enstatite.

[31] I find no reason in the criticisms of Quirke (*Economic Geology*, **14,** 1919 (621)) to change my oft expressed views regarding the origin of the metallic iron through the reduction of lawrencite or some other easily reducible compound. Chlorine is a gas and in a dry atmosphere would readily escape of itself and without evident action on the silicate constituents. If means were to be "provided" it would have to be for the retention rather than for getting rid of this constituent.

[32] *C. R. Paris Acad. Sci.*, **13,** 1841 (48).

[33] *Jour. Proc. Roy. Soc., New South Wales*, **36,** 1902.